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10.4 Experience of Beryllium Blocks Operation in the SM and MIR Nuclear Reactors useful for Fusion

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The results are presented concerning the examinations of state of beryllium blocks after the completion of their operation in the SM and MIR reactors. Both cracks and more significant mechanical damages are revealed in the irradiated beryllium blocks. Under neutron irradiation of beryllium radiation degradation of its physical and mechanical properties occurs. It shows itself in embrittlement, decrease of brittle strength level as well in worsening of thermal conductivity that leads to increase of thermal stresses into beryllium block. Under irradiation it takes place damage of beryllium microstructure, in particular, formation of radiation defects occurs in the form of dislocation loops and great amount of helium atoms. Optimization of beryllium radioactive waste storage is related to their preliminary surface and volumetric decontamination.

1. INTRODUCTION

At present more than 20 nuclear reactors are available in the world, in which beryllium is used as a material of neutron reflector or moderator. At the Research Institute of Atomic Reactors two research reactors of this type, SM and MIR, have been operated within several decades. Application of beryllium in these reactors allows, using its specific neutron physical characteristics, to create a neutron field with the specified parameters in the core.

Nevertheless, usage of beryllium under neutron irradiation conditions possesses some difficulties, the main of which is its susceptibility to significant radiation damage, necessity of periodical storage of large amount of high-active beryllium waste and some other. This paper presents the description of the state of irradiated beryllium blocks after operation up to resource neutron fluence. Also, the results are presented concerning the examination of radiation changes of the TE-56 beryllium grade properties, which is applied in the Russian reactors as a beryllium block material. Undoubtedly, vast experience of beryllium application under conditions of high-flux irradiation by high-energy neutrons should be taken into account in evaluation and verification of possibility of beryllium application as a material of some fusion reactor components.

2. PARAMETERS OF BERYLLIUM BLOCKS OPERATION IN THE SM AND MIR REACTORS

Figure 1 (a) presents the transversal cross-section of the SM reactor core. Table 1 presents its main technical characteristics. Up to now, the SM reactor has the highest neutron flux in the world and that is why, it is of great interest as a testing area for fusion reactor materials. The highest fast neutron flux is in the reactor core; it achieves $2\cdot10^{15}cm^{-2}$ (E>0.1 MeV). Such high neutron flux is created by means of beryllium reflector, which is located over the core perimeter. Beryllium blocks of the first row, the nearest to the core, are subjected to the most significant radiation damage (Fig.1(b)). There is a central block of transuranic targets in the core center. It comprises four beryllium blocks used as a neutron moderator (Fig.1(c)). As a result, high thermal neutron flux is generated in the area limited by these four blocks that provides high effectiveness of radioactive isotope accumulation in the central cylindrical cavity of the SM reactor core.

Table 1
The main technical characteristics of the SM reactor

Characteristics	Unit	Value
Thermal capacity	MW	100
Maximum thermal neutron flux	neutron/cm^2·c	$5\cdot10^{15}$
Maximum fast neutron flux (E>0.1 MeV)	neutron/cm^2·c	$2\cdot10^{15}$
Core volume	l	51.9
Core height	m	0.35
Average thermal loading of the core	MW/l	2
Maximum thermal loading of the core	MW/l	10
Fuel	Cermet with uranium dioxide	
Coolant	Water	
Moderator	Beryllium, water	
Reflector	Beryllium	
Coolant temperature	°C	50-95
Pressure	MPa	4.9
Duration of micro-run	day	10-14
Reactor run duration	day	50

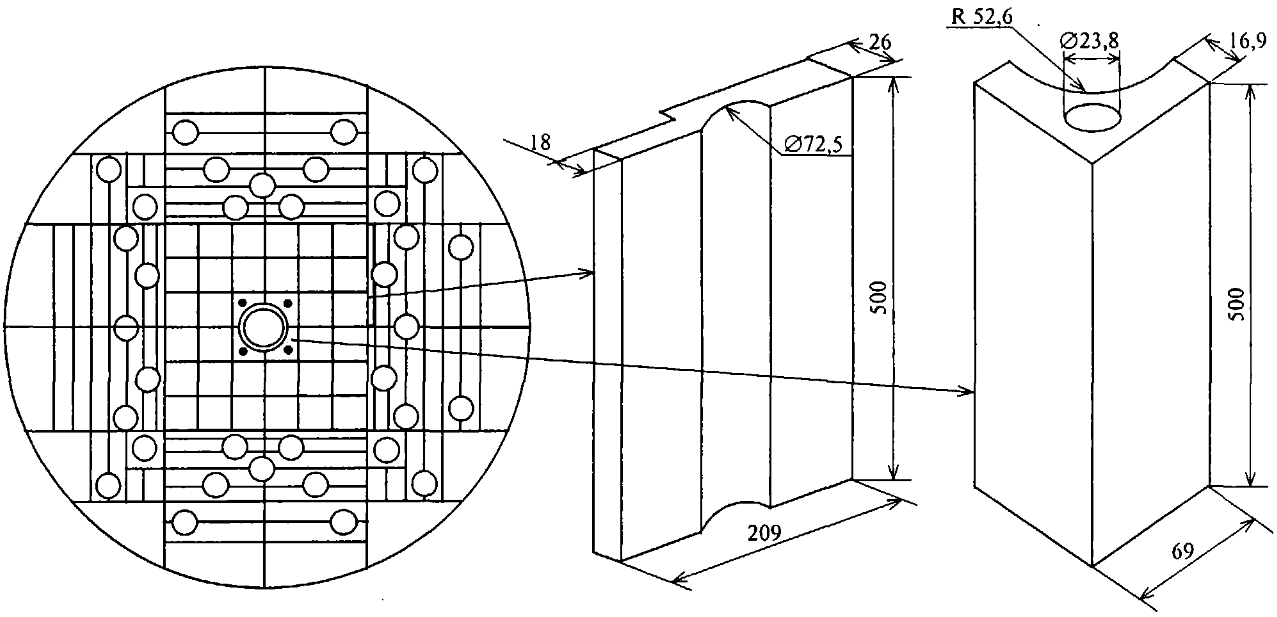

Figure 1. The SM reactor core:
a) transversal cross-section of core;
b) reflector beryllium block;
c) central beryllium block

The MIR reactor core is located in the pool filled with water. It consists of hexagonal beryllium blocks. The transversal cross-section of the MIR core is presented in Fig.2 (a) and the main reactor characteristics are presented in Table 2. The channel design of the reactor provides for location of each fuel assembly in separate channel located inside each beryllium block. The control rods are located in the holes at the joint of the neighboring beryllium blocks edges. Thus, the beryllium block of the MIR reactor core has a rather complicated shape (Fig.2 (b)).

Table 2
The main technical characteristics of the MIR reactor

Characteristics	Unit	Value
Thermal capacity	MW	100
Maximum thermal neutron flux	neutron/cm^2·c	$5\cdot 10^{14}$
Fuel	Metal-ceramics on the basis of uranium dioxide	
Coolant		Water
Moderator		Beryllium
Reflector		Beryllium
Coolant temperature	°C	40-98
Pressure	MPa	1.5
Reactor run duration	day	30-40

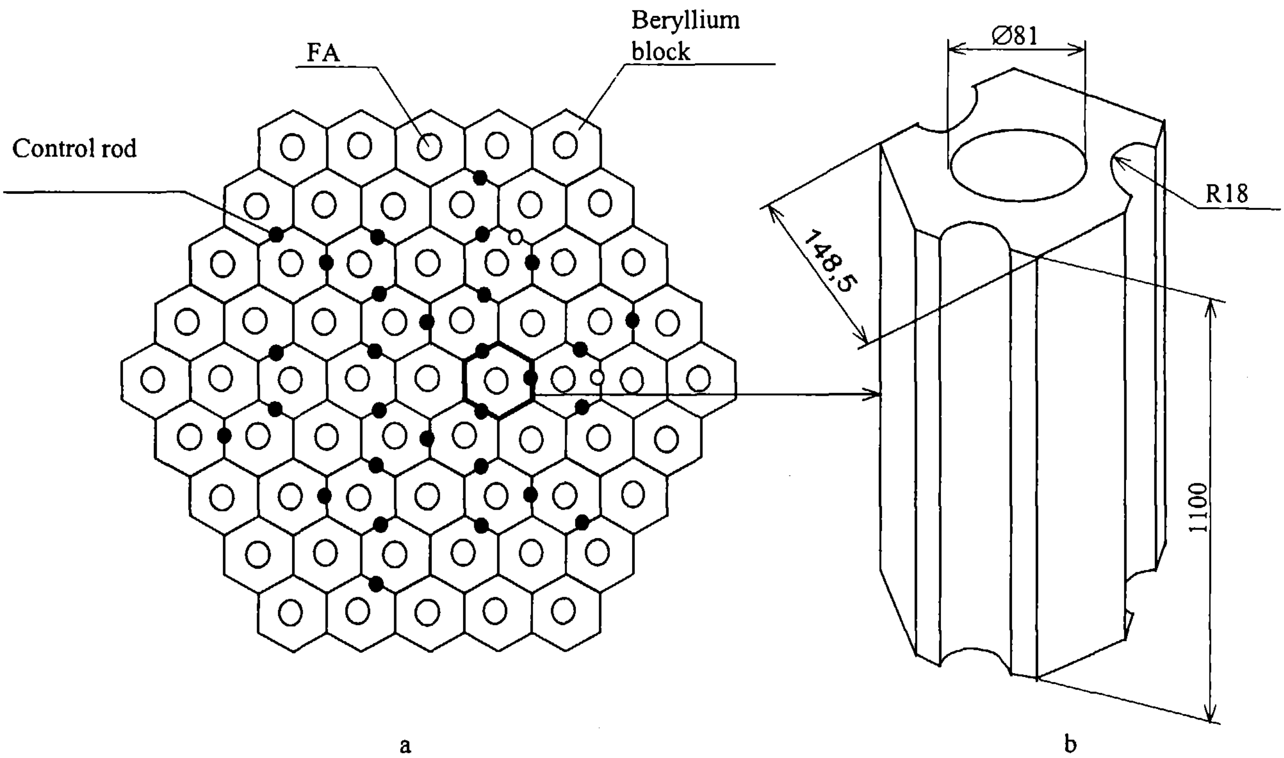

Figure 2. The MIR reactor core:
a) transversal cross-section of core;
b) beryllium block of the core laying

At present, the TE-56 beryllium grade is used as a block material. Its chemical composition and grain size is presented in Table 3. The blocks are fabricated from hot-pressed blanks using technology of hot extrusion (HE). Nevertheless, at the first stages of the MIR reactor operation in the past beryllium of lower quality was used. As for the SM reactor, beryllium oxide was used (Table 4). Four reconstructions of the SM reactor and one of the MIR reactor were performed within the whole operation period. As a result, the core parameters were improved and the reactor operation safety was increased.

Table 3
Chemical composition of the TE-56 beryllium grade

Technology	Maximum grain size, μm	Average grain size, μm	Element content, % mass						
HE	56	25	Be	BeO	O	C	Fe	Al	Si
			98.6	1.48	0.98	0.08	0.17	0.026	0.016

Table 4
Chronology of beryllium block application in the SM and MIR reactors

Reactor	Beryllium loading into reactor		Status of beryllium blocks in the core
	Year	Material, grade	
SM	1961	Beryllium oxide	Reflector and central blocks (moderator)
	1974	Hot-pressed beryllium with grain size ≤ 400μm	
	1991-1993	HE technology, grain size ≤ 56μm	
	2005-2006	HE technology, grain size ≤ 56μm	
MIR	1966	Hot-pressed beryllium with grain size ≤ 400μm	Laying of hexagonal core blocks
	1975-1976	Hot-pressed beryllium with grain size ≤ 400μm	
	1994-2000	HE technology, grain size ≤ 56μm	

3. ASSESSMENT OF BERYLLIUM BLOCKS STATE AFTER COMPLETION OF THEIR OPERATION IN REACTOR

At present, according to the norms of beryllium block operation in the SM and MIR reactors, the maximum resource fluence of $6 \cdot 10^{22} cm^{-2}$ (E>0.1 MeV) is specified for the blocks located in the core. Nevertheless, the block can be unloaded earlier, before the achievement of this fluence, in case of its mechanical damage revealed in the course of periodical visual inspection. The accumulated vast experience on examination of the state of irradiated beryllium blocks allows for drawing a conclusion that the time of beginning of beryllium block mechanical damage during its operation in the reactor is not stable. In some cases, the first cracks in the blocks can appear even after achievement of neutron fluence of $(2\text{-}4) \cdot 10^{22} cm^{-2}$ (E>0.1 MeV). Nevertheless, there are some cases when the block preserved its integrity and there were no any cracks in it even at the resource neutron fluence. But in most cases both cracks and other significant mechanical damages are observed in the beryllium block when the fluence of $\sim 6 \cdot 10^{22} cm^{-2}$ (E>0.1 MeV) is achieved.

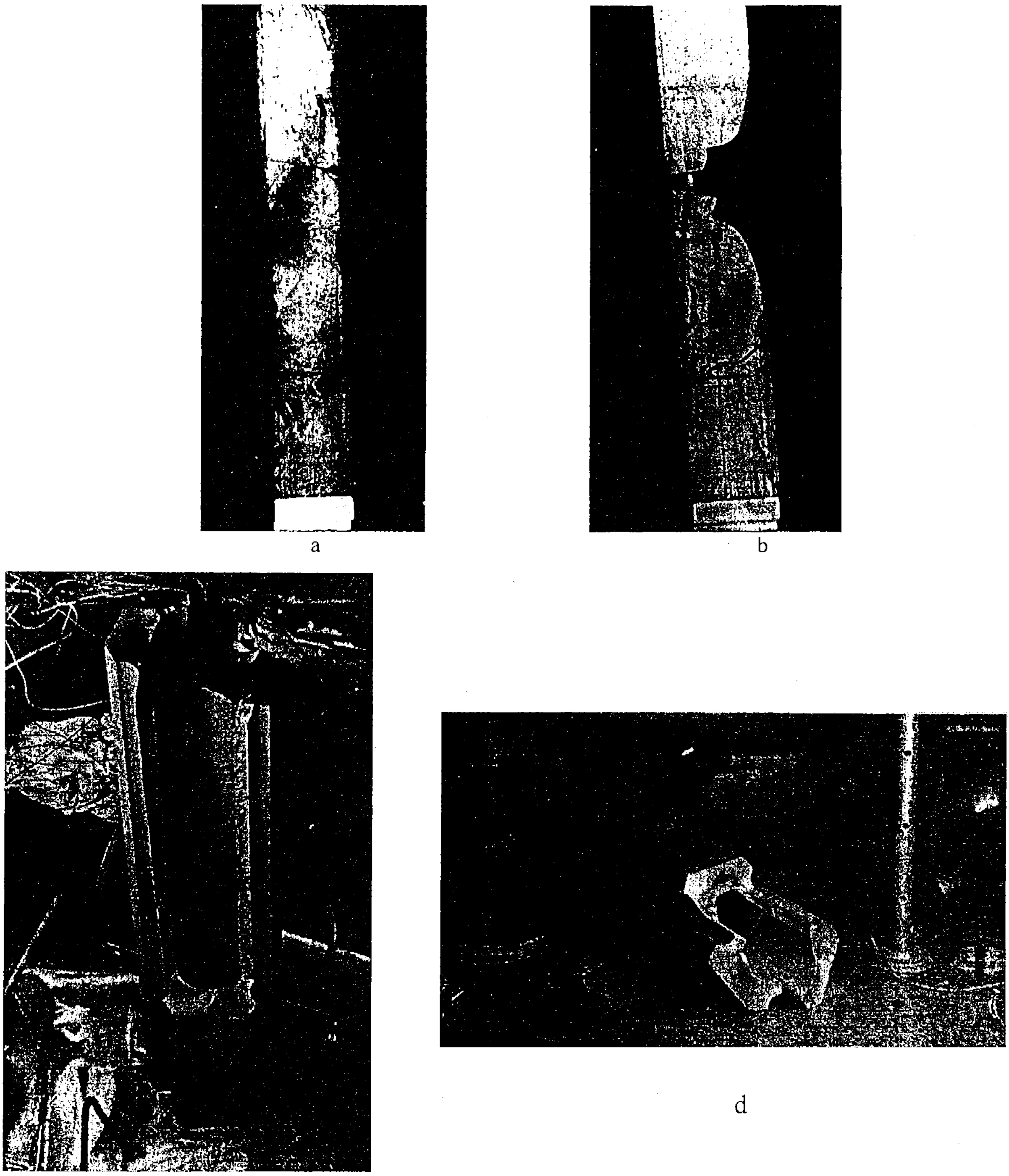

Figure 3. Appearance of beryllium blocks irradiated up to resource neutron fluence F~6×10^{22} cm^{-2} (E>0,1 MeV):
a,b) blocks of the SM reactor;
c,d) blocks of the MIR reactor

Figure 3 presents the appearance of the irradiated beryllium block of the SM reactor unloaded from the reactor when the maximum resource fluence is achieved. One of the blocks (Fig.3(a)) preserved practically its integrity but there are some transversal cracks located in the places corresponding to the upper and lower core boundaries. The other block (Fig.3(b)), along with cracks, has significant damages in its central part, i.e. one block fragment is absent. The block preserved stable state and did not break into separate parts only owing to the presence of the supporting tube passing transversally through the whole block along its height. Great attention should be paid to the appearance of the outer surface of the blocks, in particular to the presence of small cavities and large dark spots. Probably, these defects appear as a result of corrosion damage of the block material in washing water coolant. As it was mentioned above, the beryllium blocks of the first row of the reflector and central blocks as well are subjected to the most intensive radiation damage in the SM reactor. Due to the presence of maximum neutron flux and, respectively, the highest rate of radiation damage accumulation in these items, their damage rate is the maximum one. The periodicity of the replacement of the most intense beryllium blocks of the SM reactor is 1.5-2.5 years.

As for the MIR reactor, the beryllium blocks are operated under rather less intense conditions. That is why they can be replaced every 15-25 years depending on their state after long-term irradiation. The most characteristic defects of the mechanical damage of the MIR reactor blocks are cracks of transversal orientation appearing in the cylindrical slots along the edges, i.e. in the places of the least block wall thickness. As a rule, the block preserves its integrity in the core when the resource fluence is achieved. Nevertheless, during transport operations the irradiated block can likely break into large fragments. Figure 3 (c,d) presents the appearance of fragments of the damaged beryllium blocks that were transported to the hot cell.

4. EXAMINATION OF MATERIAL OF REFLECTOR AND MODERATOR BLOCKS

The results of examination of the TE-56 beryllium grade radiation damage performed recently [1-3] show that with the increase of neutron dose a significant degradation of beryllium physical and mechanical properties occurs. In particular, beryllium swelling can achieve 1.5-2% at dose that exceeds by about two times the resource one (Fig.4).

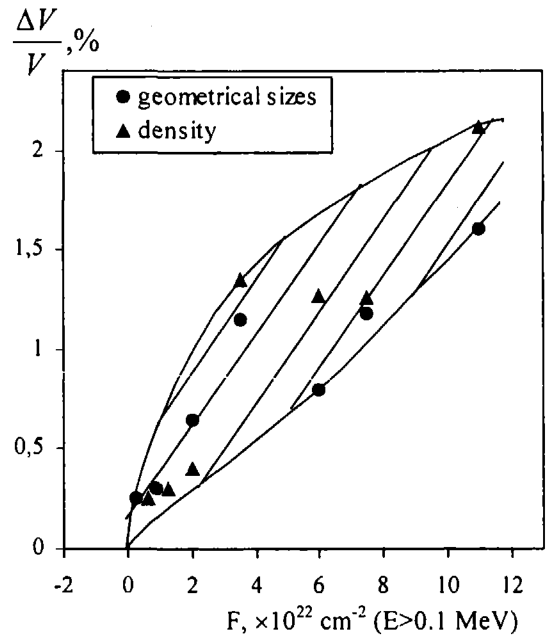

Figure 4. Dose dependence of swelling for the TE-56 beryllium grade irradiated at 70°C

At the resource dose ($6\cdot10^{22}cm^{-2}$ (E>0.1 MeV)) swelling achieves ~1 %. Being not so significant, this swelling has serious consequences that show themselves in strong radiation embrittlement and further decrease of brittle strength [4]. It occurs due to anisotropy of swelling of separate beryllium crystals in the product bulk and absence of relaxation of appearing grain-boundary stresses owing to low irradiation temperatures. The dose dependence of beryllium brittle strength is presented in Fig.5. It can be seen that the main strength decrease occurs in the dose range from zero to $2\cdot10^{22}cm^{-2}$ (E>0.1 MeV) [5,6]. Here, the difference in the brittle strength value of the irradiated specimens cut off along and across the extrusion axis is preserved up to dose of ~$8\cdot10^{22}cm^{-2}$ (E>0.1 MeV). This is the evidence of the significant radiation damage anisotropy of the TE-56 beryllium grade fabricated by the hot extrusion technology. The attention should be paid to the fact that according to the tensile tests of the specimens preliminary fabricated and then irradiated in special capsules, the strength margin of 100 MPa that exceed by about two times the resource ones is retained at the level of the achieved neutron doses

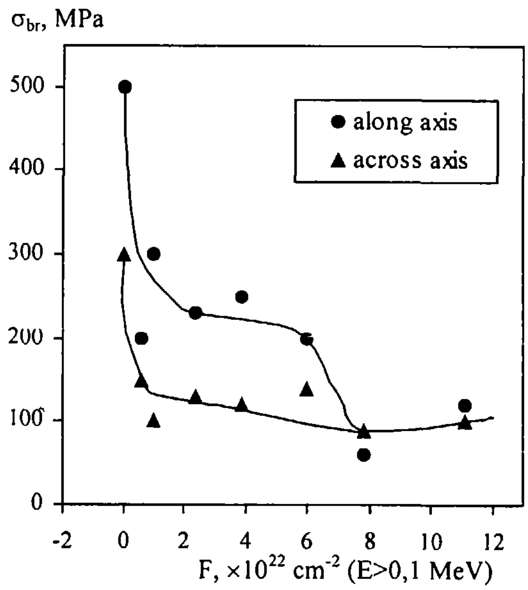

Figure 5. Dose dependence of brittle strength (σ_{br}) for the irradiated TE-56 beryllium grade (T_{irr}=70^{0}C, T_{test}=20^{0}C) according to mechanical tensile tests

The reactor beryllium block has significant geometrical dimensions. Due to this fact and different ways of heat removal, non-uniformity of the temperature field on the block surface and in its bulk is observed. The available temperature gradient leads to generation of thermal stresses, of which value depends directly to the thermal-conducting properties of beryllium. It was obtained recently [7,8] that the specific thermal conductivity coefficient for the TE-56 beryllium grade decreases by several times under irradiation (Fig.6). As a consequence, inner thermal stresses increase greatly. Probably, just these stresses lead to occurrence of cracks and other mechanical damages of the beryllium blocks when they are in a reactor. But the positive moment is still stabilization of thermal conductivity of irradiated beryllium at a certain level with the growth of dose. As in the case of mechanical properties, the main thermal conductivity drop occurs in the dose range from zero to $2\cdot10^{22}$cm^{-2} (E>0.1 MeV).

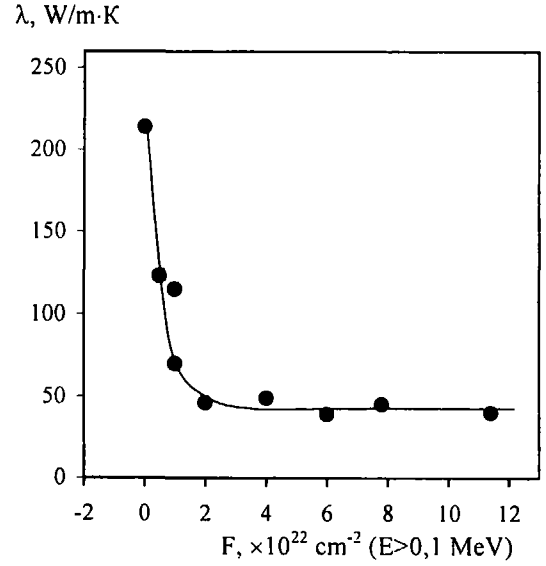

Figure 6. Dose dependence of thermal conductivity for the TE-56 beryllium grade, along the axis at T_{irr}=T_{test}=70^{0}C

The causes of degradation of beryllium physical and mechanical properties are significant changes in beryllium microstructure under irradiation. As it is known [9], the main features of radiation damage of beryllium microstructure under low-temperature irradiation are generation of radiation defects in the form of dislocation loops as well as transmutation of large amount of helium and hydrogen isotopes. The latter phenomenon also takes place under high-temperature irradiation but at low temperatures generated helium atoms remain in the places of their generation due to lower diffusion mobility. This fact leads to occurrence of additional inner stresses caused by significant crystalline lattice distortion.

5. STORAGE OF IRRADIATED BERYLLIUM BLOCKS

After completion of irradiation in a reactor, the beryllium block has high-induced activity and it is stored in the high-active waste storage facility. This procedure is not optimal since the volume of the storage facility is limited and it is intended, first of all, for storage of spent fuel-containing core components. The basic operation in storage of this radioactive waste is their location in special storage bins and further filling with concrete.

Optimization of beryllium radioactive waste storage supposes the decrease of their induced-activity level. It is possible if surface and volumetric decontamination of the irradiated beryllium blocks is performed. The first stage is decontamination of the block surfaces from radioactive substances, which can occur there during the block operation in the reactor and due to the contact with water coolant of the primary circuit. At the second stage it is necessary to remove radiogenic impurities from the block bulk. In particular, gaseous tritium can be removed from the irradiated material by high-temperature annealing. Table 5 presents the results of mass-spectrometric measurements of residual content of ^{4}He and T in the cylindrical beryllium specimen irradiated at 70°C up to neutron fluence $4\cdot10^{22}$ cm^{-2} (E>0.1 MeV) and further repeated one-hour annealing at 500-1200°C. As for this experiment, the beginning of irradiated beryllium degassing is observed at 500°C. There are no tritium traces in the irradiated specimen after annealing at 1000°C. Here, the outer part of the cylindrical specimen Ø6x8mm is subjected to degassing to a greater degree as compared to the inner part. The removal of radioactive metallic impurities from irradiated beryllium can be a great problem. Probably, it is possible only using chemical methods.

Table 5
Content of helium and tritium in beryllium irradiated at 70°C up to neutron fluence $4\cdot10^{22}$ cm^{-2} (E>0.1 MeV) after isothermal annealing.

Annealing temperature, ^{0}C	^{4}He content in specimen, appm		Relation of intensity peaks ^{4}He/T
	Inner part of specimen	Outer part of specimen	
Without annealing	5 453 ± 264	5 127 ± 257	8,0
700	5 266 ± 239	4 341 ± 209	54,6
800	4 894 ± 214	3 748 ± 167	90,9
1000	3 770 ± 401	2 532 ± 239	no T peak
1100	72 ± 4	34 ± 3	no T peak
1200	47 ± 2	35 ± 2	no T peak

6. CONCLUSIONS

1. Examinations of the state of beryllium blocks were performed after completion of their operation in the SM and MIR reactors. As a rule, there are both cracks and more significant mechanical damages in the irradiated beryllium blocks, when fluence ~$6\cdot10^{22}$cm^{-2} (E>0.1 MeV) is achieved.
2. Radiation degradation of the mechanical and physical properties of beryllium shows itself in embrittlement, decrease of brittle strength level and sharp drop of thermal conductivity that leads to the growth of inner thermal stresses in the beryllium block bulk. It is determined by the effect of low-temperature neutron irradiation on the beryllium microstructure that leads to generation of radiation defects in the form of dislocation loops and large amount of helium.
3. Optimization of beryllium radioactive waste storage is related to performance of preliminary surface and volumetric decontamination of the irradiated beryllium block material. It allows to decrease significantly the beryllium block activity and convert them into category of low-active waste.

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